Paul Robinson

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
Salt Lake City Metallurgy Research Center
1600 East 1st South Street
Salt Lake City, Utah 84112

Joe B. Rosenbaum, Research Director

METHODS AND COSTS FOR STABILIZING TAILINGS PONDS

by

Karl C. Dean and Richard Havens

Presented at the American Mining Congress
Mining Convention/Environment Show
Denver, Colo., September 9-12, 1973

0002

METHODS AND COSTS FOR STABILIZING TAILINGS PONDS

by

Karl C. Dean[1] and Richard Havens[1]

ABSTRACT

Fine-sized mineral wastes discarded by ore milling plants require stabilization to prevent air and water pollution. Methods devised for achieving this stabilization include physical, chemical, vegetative, and combination procedures. Although vegetative reclamation is preferred to physical and chemical stabilization, it is difficult to achieve because the wastes are sterile, contain deleterious inorganic salts, and lack the essential nutrients and physical characteristics required for sustaining vegetative growth. Nevertheless, recent research has developed methods for producing vegetative growth on all but excessively acidic, basic, or saline tailings at costs ranging from $100 to $650 per acre. This report summarizes effective procedures developed by the Federal Bureau of Mines for vegetating average tailings, the cost differential between the various methods, and suggests procedures that may be applicable for achieving stabilization of pyrite-containing wastes that may oxidize and become excessively acidic. The use of buried layers of sewage sludge to prevent this acidification is discussed.

INTRODUCTION

About 1.7 billion tons of mineral wastes are discarded annually in the United States. The total accumulated mineral solid wastes amount to about 25 billion tons. These mineral waste piles currently cover over 2 million acres of land. They are second only to agricultural wastes in quantity and represent nearly 40 percent of the total solid wastes produced in the United States. A part of the mineral discard is fine-size material requiring some sort of stabilization if air and water pollution are to be minimized. On active mill tailing ponds, air pollution is controlled by keeping the surfaces of the ponds wet either by tailings discharge or by sprinkling. On inactive ponds, a more permanent solution is required, usually that of physical, chemical, or vegetative stabilization.

1/ Metallurgist, Salt Lake City Metallurgy Research Center, Bureau of Mines, U.S. Department of the Interior, Salt Lake City, Utah.

Other physical methods of stabilization evaluated include (1) the use of bark covering and (2) the harrowing of straw into the top few inches of tailings.

Chemical Stabilization

Chemical stabilization involves reacting a reagent with mineral wastes to form an air- and water-resistant crust or layer that will effectively stop dusts from blowing and inhibit water erosion. Chemicals have the drawback of not being as permanent a stabilizing means as soil covering or vegetation. However, chemicals can be used on sites unsuited to the growth of vegetation because of harsh climatic conditions or the presence of vegetable poisons in the tailings, or in areas that lack access to a soil-covering material. Chemical stabilization is also applicable for erosion control on active tailings ponds. Chemicals can be effectively used on portions of these ponds to restrict air pollution while other portions continue to be active.

Seventy chemicals have been tested in the laboratory, and selected materials have been tested in field plots. Optimum conditions and effective rates of application for all materials tested have not been determined, and testing is continuing. The more effective chemicals of those tested are listed in order of effectiveness based upon the cost in cents for the amount of reagent required to stabilize 1 square yard. An overlapping of costs resulted because some of the reagents were required in greater quantities to stabilize different tailings. The general conclusions derived from tests conducted to date are as follows:

1. Coherex[2/], a resinous adhesive, furnished wind-resistant tailings surfaces when applied in quantities costing as little as $0.01 per square yard, but resistance to water-jet testing was not achieved until reagent costing about $0.10 per square yard was applied.

2. Calcium, ammonium, and sodium lignosulfonates, as well as redwood bark extracts, were all effective surface stabilizers at costs of about $0.02 per square yard.

3. Cement and milk of lime additives were effective in stabilizing surfaces when applied in amounts costing $0.03 per square yard.

4. Paracol S 1461 (a blend of wax and resin) and Paracol TC 1842 (a resin emulsion) were effective as stabilizers in quantities ranging in cost from $0.04 to $0.10 per square yard on various tailings samples tested.

2/ Reference to trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

5. Potassium silicates having SiO_2-K_2O ratios of 2.5 were effective stabilizers when applied at a rate of $0.07 to $0.15 per square yard.

6. A cationic neoprene emulsion and Rezosol, an organic polymer, effectively stabilized tailings at costs approximating $0.08 per square yard.

7. Sodium silicate applied in quantities of 4.5 pounds per square yard at a cost of $0.11 per square yard was an effective stabilizer. Calcium chloride was an effective additive to the sodium silicate, whereas ferrous sulfate was not. The addition of 6 percent by weight of $CaCl_2$ permitted reduction of the cost of sodium silicate used from $0.11 to $0.02 per square yard.

8. Peneprime (a bituminous base product), selected amines, dicalcium silicate, and elastomeric polymers (Compound SP-400, Soil Gard, and DCA-70) produced wind- and water-resistant surfaces at costs of $0.10 per square yard and up.

9. Pyrite treated with sulfuric acid, Aerospray Binder 52 (a synthetic resin), Landscape (a solution of combined sulfur in water-soluble oil), or Water Mate (an organic, nonionic product) were ineffective on the tailings used in the testing.

Vegetative Stabilization

The successful initiation and perpetuation of vegetation on fine wastes involves ameliorating a number of adverse factors. Mill wastes usually (1) are deficient in plant nutrients, (2) contain excessive salts and heavy metal phytotoxicants, (3) consist of unconsolidated sands that, when windblown, destroy young plants by sandblasting and/or burial, and (4) lack normal microbial populations. Other less easily defined problems also complicate vegetative procedures. The sloping sides of waste piles receive greatly varying amounts of solar radiation depending on direction of exposure. Studies by Gates[3] have indicated that, contrary to popular belief, photosynthesis of plants is not continuous while the sun is shining; under high-temperature conditions, photosynthesis may almost stop. Furthermore, most accumulations of mill tailings are light in color and may reflect excessive radiation to plant surfaces, thus intensifying physiological stresses. For these reasons, vegetation that may be effective on northern and eastern exposures may not be suitable for southern or western exposures.

Ideally, vegetative stabilization should produce a self-perpetuating plant cover directly or foster entrapment and germination of native plant seeds, which will form a self-regenerating community. In the latter case, an ecological succession would be established leading to a vegetative covering so completely in harmony with the environment that irrigation or special care would be unnecessary. If the area were not cropped or grazed, only an initial fertilization should be required because the essential nutrients would be largely cycled in place.

3/ Gates, David M. Radiant Energy, Its Reception and Disposal. Meteorological Monograph 28, v. 6, 1965, pp. 1-26.

Research indicates that, other than the excessive acidity, basicity, or salinity, perhaps the greatest problem to be overcome in establishing vegetation is that of windblown sands. Several approaches have been postulated for preventing windblown sands from covering or cutting off the growing plants. Extensive water sprinkling while the plants are growing, covering the tailings with soil or country rock, hydroseeding, using excelsior-filled matting as a cover directly over the tailings, and a combination chemical-vegetative procedure developed by the Bureau of Mines are suggested procedures. Sprinkling, soil covering, hydroseeding, and matting have all been proved on various types of wastes, and the chemical-vegetative procedure has proved effective during the past 4 years on six different tailings ponds.

The hydroseeding procedure as normally used encompasses blowing a slurry of wood chips or paper pulp with admixed seeds and fertilizer over the surface to be stabilized. After the seeds germinate, the wood chips or paper pulp serve as protection for the seedlings and inhibit the blowing of sands. Matting serves the same purpose as the wood chips for that method. Usually the area is planted with seeds and fertilizer, and then 3-foot-wide strips of excelsior-filled matting are staked continuously or at 3-foot intervals over the planted area. Matting is used most commonly on the sloping surface of tailing dikes to inhibit slippage of the sands.

The Bureau-developed chemical-vegetative procedure involves the application of a small amount of chemicals to newly planted tailings to achieve several worthwhile goals. Sand blasting of plants is minimized. Moisture is retained in the tailings. Germination is promoted and wilting minimized by creating a dark, heat-absorbing, nonreflecting surface.

The procedure ultimately developed from laboratory testing involved planting the tailings with a mixture of fertilizer and grass, legume, and grain seeds, watering the plot, and applying a stabilizing chemical in water solution. Early fertilization tests showed that all tailings required nitrogen and phosphorus additions, but that nitrogen in quantities of more than 45 pounds per acre seriously hampered legume seed germination. Hence, most tailings were fertilized with 30 and 75 pounds per acre, respectively, of nitrogen and P_2O_5. A few tailings required potassium in which case up to 40 pounds of potassium per acre were added. All seeds used for planting were selected for compatibility with the particular climatic environment in which the tailings are located. A suitable grain was added to the seed mixture to provide early growth for assisting the chemical in stabilizing the surface. The chemical, preferably thus far a resinous adhesive type, was applied to the moistened tailings in amounts costing 1 cent or less per square yard. This stabilization procedure generally is best applied in the fall of the year so as to achieve some growth before the onset of winter, thus allowing the root system to develop under a cover of snow and with good moisture conditions.

The chemical-vegetative procedure has been effectively applied to copper, lead-zinc, uranium, and clay tailings under widely different climatic conditions existing in Colorado, Michigan, Missouri, Nevada, and Washington.

COMPARATIVE COSTS

Mining companies have tested many of the outlined procedures for stabilizing and reclaiming mineral wastes. Stabilization costs using various procedures are shown in table 1. In general, costs for reclaiming sloping dike areas have been about 25 percent greater than costs for flat pond areas. The costs given in table 1 are estimated for a tailings accumulation consisting of 80 and 20 percent, respectively, of pond and dike areas. These costs, although broadly generalized, provide some comparison of different methods.

These data indicate that several methods are available for stabilizing mill tailings at costs of less than $400 per acre. The chemical-vegetative procedure appears to be the most economical procedure for establishing vegetation on tailings and wherever applicable should be a preferred method. Where prevention of blowing sands is the major problem in achieving stabilization, both the chemical-vegetative and hydroseeding methods appear to be economically preferable to the matting or soil-covering procedures. However, for difficult areas, these latter methods may be mandatory.

ONGOING RESEARCH

The development of several different vegetative procedures has provided satisfactory stabilization for many of the mill tailing accumulations scattered across the country. However, many major problems still require resolution. High maintenance costs cause concern about vegetated tailing plots, but the principal problems occur in establishing vegetation on tailings of excessive salinity or acidity. Work is going on to reduce maintenance costs by reducing fertilizer requirements on vegetated plots. Research also is continuing to aid in the growth of vegetation on problem tailings by making synthetic soils from the tailings by adding sewage sludge or refuse compost.

Reducing Maintenance Costs

Practically all mill tailings are deficient in fertilizer elements, especially nitrogen. Nitrogen not only is low in most tailings, but it is also readily depleted from vegetated wastes containing heavy metal salts. This lack of nitrogen can be overcome by planting nitrogen-fixing legumes, but legume growth on tailings is difficult to perpetuate. Considerable work has been done to promote the growth of nitrogen-fixing native plant species that may be compatible with the harsh environment of tailings. Such a plant is Indian ricegrass, a desert-type plant that

TABLE 1. - Cost comparison of stabilization methods[1]

Type of stabilization	Effectiveness	Maintenance	Approximate cost per acre, dollars
Physical			
Water sprinkling.......	....Fair.....	Continual	-
Slag (9-inch depth)			
By pumping...........	....Good.....	Moderate.	$350-$ 450
By trucking..........	.... do......	...do....	950-1,050
Straw harrowing........	....Fair.....	...do....	40- 75
Bark covering..........	Good	...do....	900-1,000
Country gravel and soil			
4-inch depth.........	..Excellent..	Minimal..	250- 600
12-inch depth.........	.....do......	...do....	700-1,700
Chemical			
Elastomeric polymer....	....Good.....	Moderate.	300- 750
Lignosulfonate.........	.....do......	...do....	250- 600
Vegetative			
4-inch soil cover and vegetation[2]....	..Excellent..	Minimal..	300- 650
12-inch soil cover and vegetation..........	.....do......	...do....	750-1,750
Hydroseeding.........	.....do......	...do....	200- 450
Matting[3]............	.....do......	...do....	600- 750
Chemical-vegetative....	.....do......	...do....	100- 250

1/ Based on average tailings, costs could be revised upwards for acidic tailings requiring limestone or other neutralizing additives.

2/ Generally used on pond area rather than on dikes. Also, not as effective as 12-inch soil cover when tailings are excessively acidic or saline.

3/ Based on placing 3-foot-wide matting at 3-foot intervals over the seeded area.

fixes nitrogen in a root sheath of sand particles invaded by bacteria. Obtaining growth from such plants, however, is difficult to achieve, in that Indian ricegrass seeds contain a natural inhibitor that limits germination to 1 percent or less on newly matured or up to 2-year-old seeds. Seeds from this plant have been gathered during the past 2 years, and germination studies have been made in an effort to break the dormancy. Treatments by attrition grinding with quartz to break the seed covering, sulfuric acid and water soaking and boiling, and cool and below-freezing incubation were all ineffective when treating both newly matured and 2-year-old seeds. When soaking seeds less than a year old in 70 percent by volume sulfuric acid for 25 minutes at 25° C, germination was nil; and with a subsequent 24-hour soaking in 10^{-3} molar gibberelic acid or kinetin hormones in a solvent of 9 parts of dichloromethane and 1 part ethanol (1-cubic-centimeter solution per 100 seeds), the germination was still less than 5 percent. However, when using a combination acid soak followed by a soak in both gibberelic acid and kinetin, the germination after 2-, 4-, and 6-week intervals, was in percent, 55, 75, and 90, respectively. When treating 2-year-old seeds, treatments with an acid soak plus respective treatments with kinetin, gibberelic acid, or gibberelic acid plus kinetin gave 5-week percentage germination rates of 5, 80, and 80, respectively. Thus, it appears that after 2 years of aging, the inhibitor effect decreases, and kinetin treatment is no longer necessary. Breaking the dormancy of Indian ricegrass seeds offers substantial promise for initiating this type of growth on adverse tailing materials, thus offering the potential of reducing nitrogen fertilizer requirements markedly with an attendant drop in maintenance costs. Tests are underway to determine if properly treated seeds can be germinated and growth sustained in adverse tailing materials.

Vegetating Adverse Tailings

Practically all mill tailings contain deleterious inorganic salts, lack organic components and essential nutrients, and do not have the physical nature required for sustaining vegetative growth. For average tailings, these adverse conditions can be overcome in time by fertilization, gradual buildup of organic and microbial populations by encouraging plant growth, and use of chemicals for binding of the surface to prevent blowing of loose sands that cut off or bury established vegetation. However, overcoming problems occasioned by excessive salinity or acidity presents a more difficult challenge. Combination problems can exist in which tailings may be excessively saline, because of the recycling of processing waters, and simultaneously contain sulfide materials such as pyrite, which upon oxidation will markedly drop the pH of the tailings to a low level in a relatively short time. Such a tailing is Kennecott's Utah Copper Division milling waste. This material with a pH of 7.8 when fresh, contains salinity equivalent to 2.4 atmospheres osmotic concentration plus approximately 1.3 percent pyrite. The salts in the tailings cause an osmotic gradient that transfers fluid from the plants, and thus vegetation deriving from seeds planted in the tailings die of dehydration.

Another problem is that, if vegetation is planted on these tailings and irrigation of the plants leaches away the salts, the pyrite will oxidize and the pH may drop from 7.8 to less than 3.0 within 1 month. Therefore, this material was considered as a typical adverse waste and was used for laboratory testing.

Buried Organic Layers

As noted, one of the major problems with growing plants on tailings is the lack of organic matter and accompanying microbial populations. Efforts were made to offset this problem by combining tailings with sewage sludge or municipal refuse compost. Preliminary, encouraging tests were made by mixing the equivalent of 15 tons per acre of these materials into the surface 2 inches of tailings. Subsequently, tests were made on pelletizing tailings with sewage sludge to form a surface layer and on the effect of buried layers of sewage sludge on the pH and salinity of the tailings being tested.

A series of tests was made in which 2-inch layers of sewage sludge were placed at different depths in barrels containing an 18-inch depth of Kennecott tailings. Sludge was placed at depths of 3, 7, 11, and 15 inches below the surface of the tailings. In another test series, the layering pattern was unchanged, but an additional equivalent of 15 tons per acre of sewage sludge was mixed into the top 3 inches of tailings. Crested wheatgrass, ranger alfalfa, and rye grain seeds were planted for both series of tests with barley used as the fourth seed in one test series, and a small transplanted tomato was used as the fourth plant variety in the other series of tests. Table 2 shows the number of plants that germinated per 100 seeds 2 weeks after planting and the number that survived at the end of 10 weeks.

The great variability in germination for the various seeds is not easily explained. Differences between series 1 and 1A, however, can be readily compared by assessing the combined results of germination and survival for the three comparable plants in each series. This shows that, of a total 1,200 wheatgrass, alfalfa, and rye seeds planted in series 1, 920 seeds germinated and 271 survived after 10 weeks to furnish a 77 percent overall germination and 23 percent survival of the total seeds planted. The results in series 1A show that with sludge present in the top 3 inches of tailing, the germination rate was 69 percent, but that the survival rate was 32 percent of the total seeds planted. Addition of sludge to the top 3 inches of tailings thus appeared to be beneficial to overall plant survival.

For evaluation of plant-species response and the effect of sludge-layer depths on germination and survival, the overall combined results from both test series were compared. These show that the combined germination and survival percentages for wheatgrass, alfalfa, and rye grain plant species were 76-29, 61-7, and 81-46, respectively. The grain and wheatgrass showed major advantages over the legumes. The overall germination and survival of plants with sewage sludge layers at depths of 3, 7, 11, and 15 inches were 71-22, 75-27, 76-27, and 70-33, respectively. These data indicate that the test with the sludge at a 3-inch depth was the poorest of the group. However, the vegetation appeared healthier in plots with the shallow sludge layers. Once the roots penetrated the sludge layer, the plants took on a much healthier appearance and were much hardier than plants with roots only in the tailings.

TABLE 2. - Germination and survival of four species of plants with 2-inch sludge layers at various depths

Depth of sludge layer below surface, inches	Number of plants							
	Crested wheatgrass		Ranger alfalfa		Rye grain		Barley grain	
	Germi-nation	Sur-vival	Germi-nation	Sur-vival	Germi-nation	Sur-vival	Germi-nation	Sur-vival
SERIES 1, NO SLUDGE ADMIXED INTO TOP 3 INCHES OF TAILINGS								
3	71	4	70	8	83	23	89	0
7	88	37	78	4	92	39	97	21
11	73	42	81	9	89	43	94	14
15	53	28	59	6	83	28	95	2
SERIES 1A, 15 TONS PER ACRE SEWAGE SLUDGE IN TOP 3 INCHES OF TAILINGS								
3	90	26	36	5	74	64	(2/)	
7	80	24	41	4	71	56		
11	78	15	59	1	78	53		
15	77	56	67	19	80	60		

1/ Germination rate at 2 weeks after planting and survival of plants after 10-week growth.

2/ Tomato plants approximately 2 inches high were planted in the fourth quadrant of the barrels.

Comparison of series 1 and 1A plots were made at 10 weeks, after which the series 1 plots were disassembled for other tests. The 1A plots were permitted to grow for 10 months to determine the effect of longevity on the plants and especially the deep-rooted tomato plant. The plots were systematically disassembled at 10 months to evaluate the plant and root systems of all the tomatoes. Results of this examination are presented in table 3.

TABLE 3. - Plant and root growth of tomatoes

Sludge position, inches	Weight of plant and recoverable roots, grams	Length of plant and main root, inches		
		Plant	Root	Total
3	1/ 411	2/ 89	19.5	2/ 108.5
7	193	64.5	54.5	119
11	97	67.5	3/ 3.25	70.25
15	69	50	32	82

1/ Includes 70 grams pruned from plant while growing so as to keep plant in bounds of plot.

2/ Does not include length of plant pruned during growing period.

3/ The main root system grew only in the surface layer of sewage sludge and tailings.

Inspection of the root systems showed that practically all roots for the sludge at depths of 7, 11, and 15 inches had grown and remained in the upper 3 inches of tailings containing admixed sludge. The main root for the 11-inch buried sludge layer had grown only 3.25 inches downward and had then sent out lateral feeder roots. The main roots in the plots with sludge layers at depths of 7 and 15 inches were much longer but grew in a circular manner, again only in the presence of the organic admixture. Conversely, the main root system for the plot with sludge at 3 inches grew down into and through the sludge layer to within 2 inches of the bottom of the tailings in the barrel. Figure 1 depicts this plant and root growth. Table 3 clearly shows the much greater plant growth attained with the sludge layer at shallow levels.

Pelletization of Tailings

Preliminary tests indicated that a better root environment and soil aeration was obtained by pelletizing the tailings. Pelletized material also appears well suited for use on tailings ponds slopes because the textured surface provides natural sites for plant growth. Therefore, a test series was made using a 1.5-inch layer of pellets on top of tailings containing sludge layers buried 3 and 15 inches under the normal tailings surface.

The pellets were minus 3/8- plus 1/8-inch size and contained, in percent, 92.4 tailings, 6.6 sewage sludge, and 1.0 chemical binder, either Coherex or Paracol TC 1842, both resinous compounds. The pellets contained the equivalent of 10.8 tons per acre of sludge in the top 1-1/2-inch layer, somewhat less than the 15 tons per acre used in the top 3 inches of tailings as in previous tests. Approximately 1-1/4 inches of pellets were distributed over the surface of the plots, the seeds were planted, and the final 1/4 inch of pellets was used as a cover for the seeds. Seeds used on each plot included crested wheatgrass, ranger alfalfa, rye grain, and alsike clover. A 2-inch tomato plant was

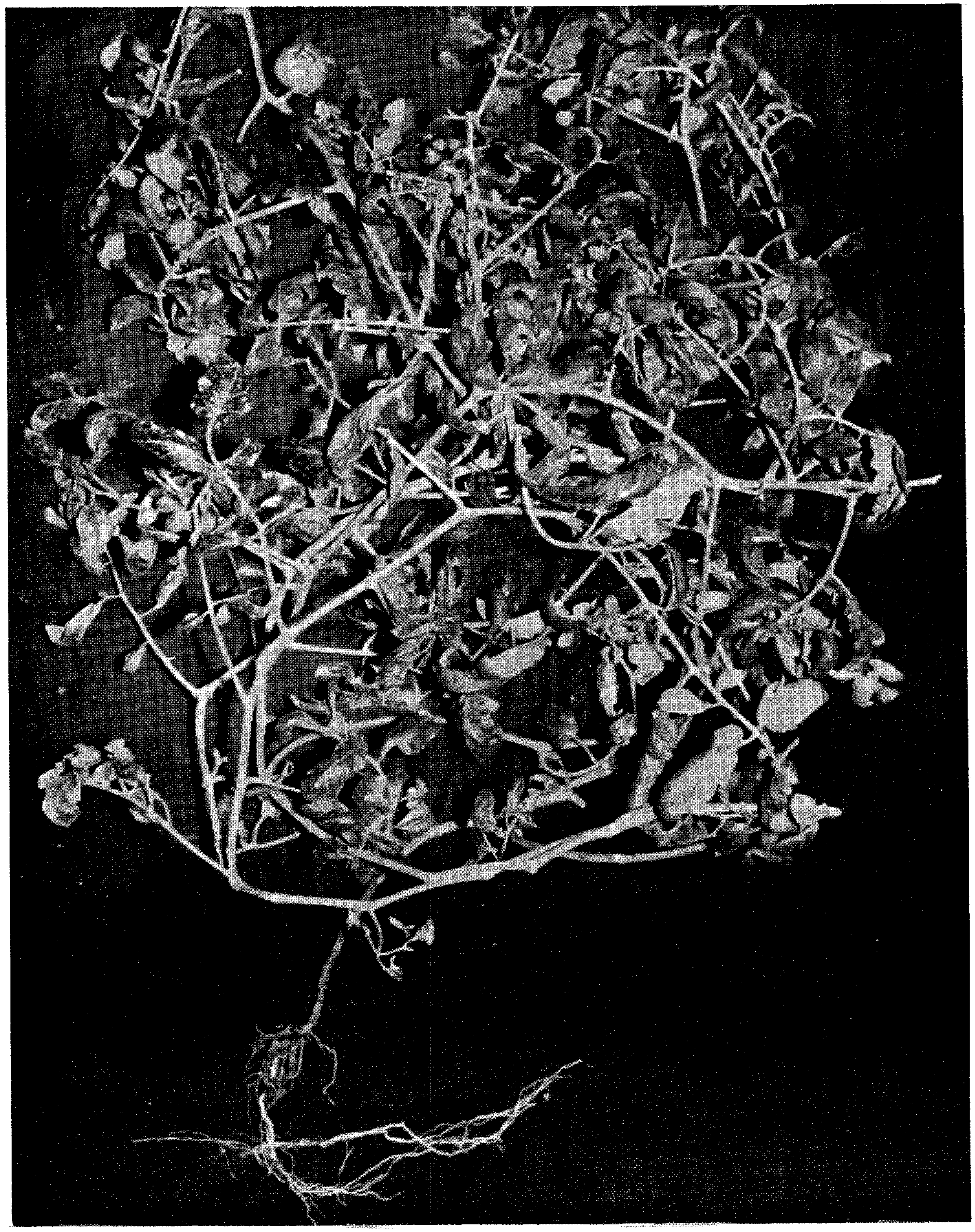

FIGURE 1. - Tomato Plant System Grown on Tailing with Sewage Sludge Layer at 3 Inches

(D-1962-SL)

also transplanted into each plot. Two plots had sludge layers 4-1/2 inches under the top of the pellet layer. The other two plots were made up similarly but with the sludge layers at 16-1/2 inches under the surface. Table 4 shows the number of plants germinating per 100 seeds 2 weeks after planting and the number surviving at the end of 10 weeks for each plot.

TABLE 4. - Germination and survival of plants with buried sludge layers and pelletized cover, percent

Type of binder	Coherex				Paracol			
Depth of sludge layer	4-1/2 inches		16-1/2 inches		4-1/2 inches		16-1/2 inches	
Plant	Germination 1/	Survival 1/	Germination	Survival	Germination	Survival	Germination	Survival
Crested wheatgrass..	79	75	82	70	72	66	79	69
Ranger alfalfa.....	57	49	67	42	70	55	58	38
Rye grain....	54	43	72	48	63	43	64	49
Alsike clover......	29	10	50	7	54	17	49	11
Tomato.......	-	1	-	1	-	1	-	1

1/ Germination rate at 2 weeks after planting and the survival of plants after 10-week growth.

As in previous tests, the germination of seeds varied broadly, and a comparison of the results was best made by comparing survival of the plants at the conclusion of 10 weeks. This comparison showed that the overall germination for all three seeds in the pelleted tailing test was 68 percent with a survival rate of 54 percent. The germination and survival rates, respectively, for the specific seeds, in percent, were wheatgrass 78-70, alfalfa 63-46, and rye 63-46. At the 10-week time interval, few differences existed in the survival of plants in the 4-1/2- and 16-1/2-inch deep buried sludge layer plots or between the two chemicals used to make the pellets. However, visual inspection of the surviving plants showed markedly better plant growth for the shallower layer and for the Coherex binder.

All plots reported on in tables 1 through 4 were maintained for at least a 10-week interval, and the results are compared in table 5.

The comparison clearly shows an advantage in adding sludge to the tailings, particularly in pelletized form.

TABLE 5. - Comparison of overall germination and survival of plants on buried sludge layer plots

Plant	Percent					
	No sludge added		Sludge mixed in top 3 inches of tailings		Sludge mixed into pellets	
	Germination[1]	Survival[1]	Germination	Survival	Germination	Survival
Crested wheatgrass..	71	28	81	30	78	70
Ranger alfalfa.....	72	7	51	7	63	46
Rye grain....	87	33	76	58	63	46
Overall......	77	23	69	32	68	54

1/ Germination rate at 2 weeks after planting and the survival of plants after 10-week growth.

Combination of Pelletization and Buried Organic Layers

A series of tests employing a combination of buried organic layers together with pelleted surface materials was established to determine the effects on vegetative growth and pH values of the component materials. Four plots were established using Kennecott tailings that had a pH of 7.8 when first obtained but which had decreased to a pH of 6.6 after several months of storage. Two replicate plots were established with a 2-inch sewage sludge layer placed under 15 inches of tailings capped by a 1-1/2-inch layer composed of, in percent, tailing 92.4, sludge 6.6, and chemical binder 1.0. The second two replicate plots were the same except that the 2-inch sewage sludge layer was placed under 3 inches of tailings and capped by pellets.

Each plot was planted with a tomato and crested wheatgrass, alfalfa, and rye grain seeds. The plants were allowed to grow for 13 months, by which time most of the wheatgrass, alfalfa, and rye had matured and died, and then the plots containing living tomato plants were dismantled and examined. The examination showed the following: (1) the root systems of all plants were principally located in the pelletized portion of the tailings, and (2) placing the sewage sludge layer at 3 inches prevented to a great extent the oxidation of pyrite in the tailings, as witnessed by an average tailings pH range of 3.9 to 6.1 and a sludge pH of 6.8 for the 3-inch-deep layer as compared with a tailings pH range of 1.7 to 2.0 and a sludge pH range of 3.6 to 4.0 for the sludge layer at 15-inch depth. A comparison of figures 2 and 3 shows the difference in pH change and moisture content within the tailings materials. Proper placement of the sewage sludge layer to control water and gas movement appears exceptionally promising for controlling the acidification of pyrite-bearing tailings.

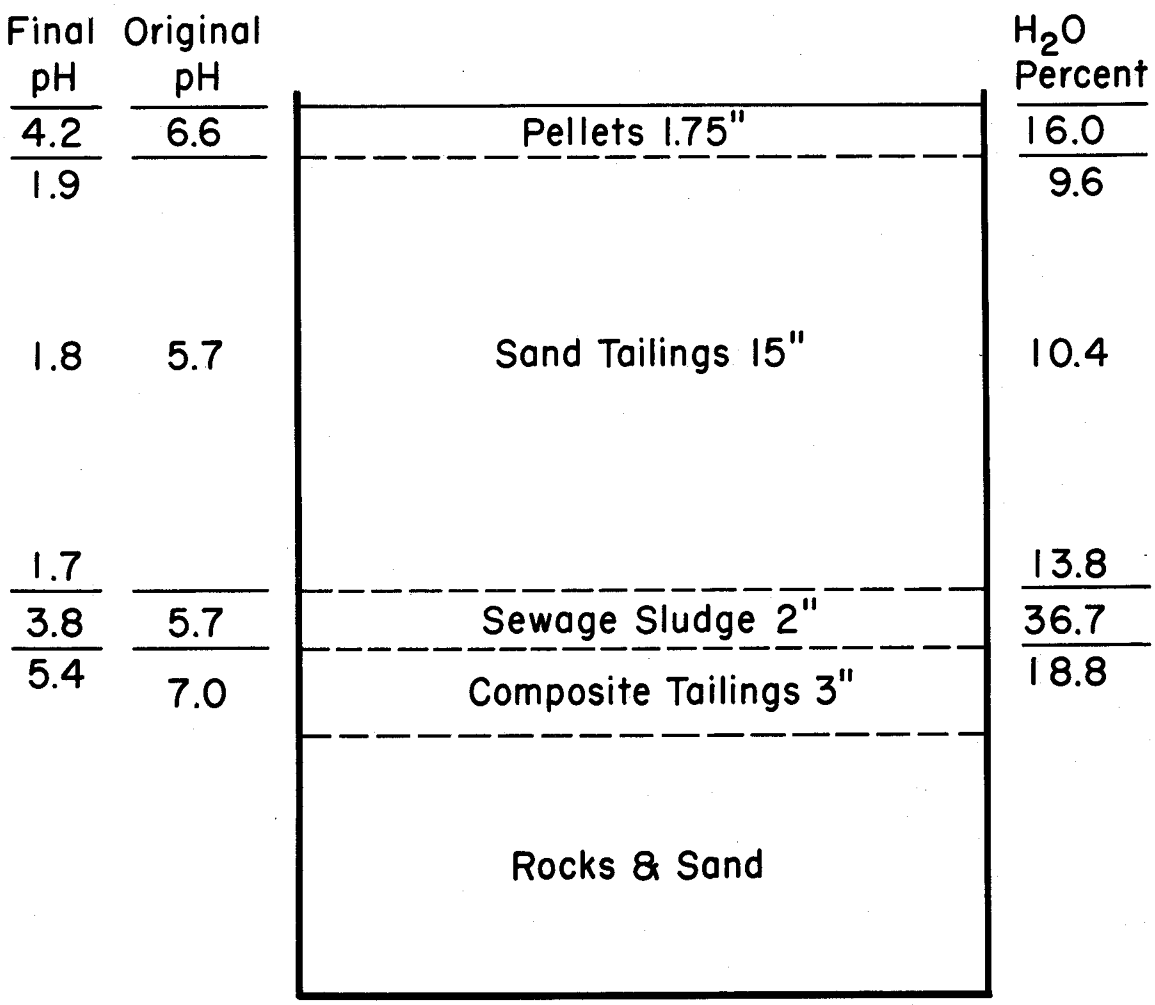

FIGURE 2. - Effect of a Buried Sewage Sludge Layer 16-3/4-inch Depth on the Oxidation of Tailing Sulfides

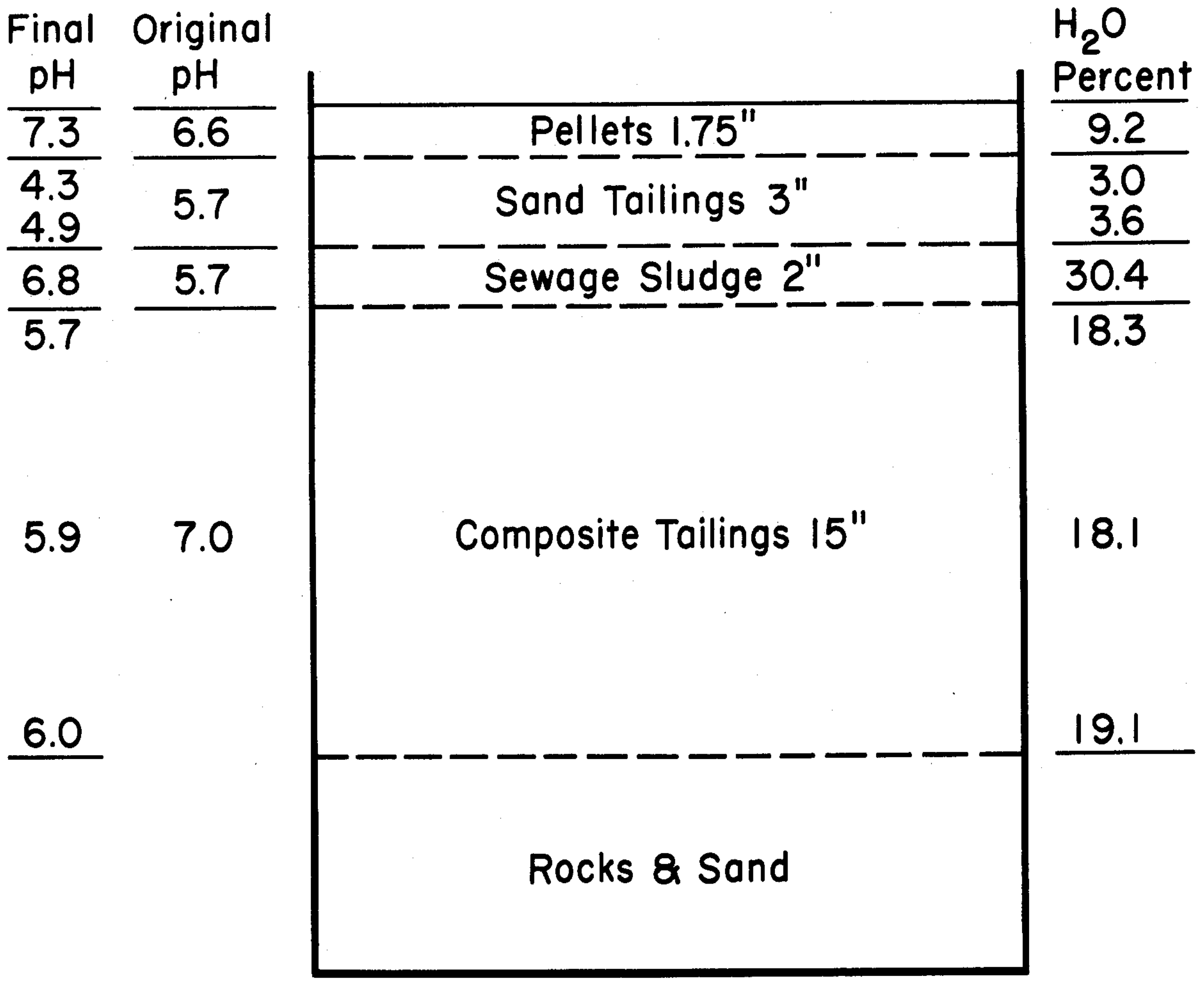

FIGURE 3. - Effect of a Buried Sewage Sludge Layer 4-3/4-inch Depth on the Oxidation of Tailing Sulfides

Costs of Projected Methods

As previously noted, several tested physical, chemical, vegetative, and combined vegetative methods have been evaluated as to stabilization effectiveness, required maintenance, and cost. The costs for the preferred vegetative methods have ranged from $100 to $1,750 per acre. Based upon the success of laboratory testing, costs were also estimated for the buried sludge layer, pelletization, and a combination method by the Bureau of Mines. The cost evaluations were made utilizing laboratory data and after consultation with firms having land-moving, transportation, and pelletizing capabilities. The following figures were basic to the Bureau evaluations: cost of sludge, $1 per ton; hauling of sludge, $0.42 per cubic yard, based on a 7-mile haul; amount of sludge per acre, 130 tons for buried layers and 11 tons for pellets; and cost of seeds, fertilizer, and planting, $50 per acre. Calculations on laying the buried sludge were made using the following: (1) an agriculturally developed method using a broad flat plow for lifting the soil and a device for spreading a layer of buried material under the low plow, and then allowing the lifted soil to drop back and bury the layered material; and (2) use of a conventional wheel scraper and spreader method. The mixture for pelletizing consisted of, in percent, 92.4 tailing, 6.6 sludge, and 1.0 chemical binder. Pelletizing was calculated as being done in place on the tailings using a recently designed high-speed light-compaction roll pelletizer, which can produce pellets at an estimated cost of $0.80 per ton. All sewage layer costs were based on application to flat pond areas only. These costs, although broadly generalized, provide a comparison for the different methods and are presented in table 6.

TABLE 6. - Cost comparison of auxiliary stabilization methods

Type of stabilization	Effectiveness	Maintenance	Approximate cost per acre, dollars
Buried sludge layers.....	Excellent	Minimal	$405- $810
Pellet cover (1-1/2 inches)	...do....	..do...	330- 660
Combined buried sludge plus pellet cover.......	...do....	..do...	735-1,470

The buried sludge layer and pelletized cover methods are still unproven in the field, and the actual costs incurred from the application of these procedures to differing sites may range to double the lower calculated figure. However, if the calculated cost range of $735 to $1,470 per acre is approximately correct for the combined buried sludge and pelleted surface method, this procedure is comparable on a cost basis to that using a 12-inch soil cover and vegetation. Tests should be made to evaluate the relative effectiveness of both procedures for

for obtaining vegetation on adverse sites. If the use of pellets is not mandatory to achieve satisfactory vegetative stabilization, then the lowered cost for application of only buried sludge layers and vegetation makes the method more competitive.